METHOD AND APPARATUS FOR LOW-SPEED, HIGH-THROUGHPUT FIBER DRAWING USING COILED FIBER LOOPS

BACKGROUND OF THE INVENTION

This invention relates to a method and apparatus for drawing fibers, yarns, or relatively narrow tapes formed from natural resin, synthetic resin, or combination of both. In the description of this invention which follows, for the sake of convenience, the method and apparatus will be described in terms of drawing fibers. However, it is to be understood that the method and apparatus are equally usable for drawing any elongated body elements subject to such procedure.

In the production of most polymer fibers (e.g., nylon, polypropylene, and polyester fibers) a drawing stage is included subsequent to the spinning or extrusion stage. In the drawing stage the fiber is usually drawn by a drawing apparatus at elevated temperature to a length substantially exceeding (in some cases, several times) their original length. The fiber passes the drawing apparatus with a speed V_{fiber} which increases from the beginning to the end of the drawing stage, speed V_{fiber} being a linear speed along the fiber axis of fiber points in the drawing process (along the tangent to the fiber axis if the fiber drawing occurs on the curved surface, e.g., a curved hot plate). A fiber draw ratio λ, which is the extent of fiber drawing, is given by

$$\lambda = V_{fiber2}/V_{fiber1}, \qquad (1)$$

where V_{fiber1} is fiber speed V_{fiber} in the beginning of the fiber drawing stage, and

V_{fiber2} is fiber speed V_{fiber} at the end of the fiber drawing stage.

The drawing of the fibers enables them to achieve the required molecular orientation and structure by virtue of which they attain the necessary strength and other desired physical characteristics. As an example, typical λ for commercial nylon fibers is about 6 to 1. Usually, the

higher the λ, the higher molecular orientation and fiber tensile properties (tenacity and Young modulus in particular).

In the case of a continuous multi-stage drawing process, V_{fiber2} is the fiber linear speed at the end of the last fiber drawing stage, and V_{fiber1} is the fiber linear speed in the beginning of the first fiber drawing stage.

The drawing has generally been hitherto effected on a commercial scale by passing the fiber from one set of rotating rollers to another. Each set of receiving rollers rotates at a surface speed which is greater than that of the preceding set of feed rollers.

In the case of drawing the fiber by the rotating rollers we get

$$V_{fiber1} = V_{surface1} = V_{intlet} \quad \text{and} \qquad (2)$$

$$V_{fiber2} = V_{surface2} = V_{outet}, \qquad (3)$$

where $V_{surface1}$ is a linear surface speed of the feed rollers,

$V_{surface2}$ is a linear surface speed of the receiving rollers,

V_{intlet} is a fiber inlet speed, which is a fiber linear speed along the fiber axis of feeding the fiber to the feed rollers, and

V_{outet} is a fiber outlet speed, which is a fiber linear speed along the fiber axis of conveying the drawn fiber from the drawing stage either to a next stage of the continuous fiber making process (drawing, heat setting, relaxation, bulking or texturing, twisting, finish application, etc.) or to a receiving package.

Thus in conventional industrial drawing processes a ratio of fiber outlet speed V_{outet} to fiber speed V_{fiber2} is 1 to 1 (this ratio will be used for discussions below).

In the case of conveying drawn fiber after the drawing stage to the receiving package we get

$$V_{fiber2} = V_{outlet} = V_{take\text{-}up}, \qquad (4)$$

where $V_{take\text{-}up}$ is a take-up speed, which is a fiber linear speed along the fiber axis of taking up the drawn fiber on the receiving package (in some cases, $V_{take\text{-}up}$ is slightly higher than V_{fiber2} and V_{outlet} to provide some tension in the taken-up fiber).

Outlet speed V_{outlet} and take-up speed $V_{take\text{-}up}$ determine the throughput of the drawing stage. Most conventional commercial processes, particularly in the area of melt-spun aliphatic polymer fibers, have very high speed $V_{take\text{-}up}$ ranging from several hundred to several thousand meters per minute to provide high throughput. This means that in these high-throughput commercial processes speeds V_{fiber2}, and V_{outlet} are also high, i.e., ranging from several hundred to several thousands meters per minute.

Another parameter is used to characterize the fiber drawing process, i.e., a relative speed of drawing or a strain rate V_{strain} which is a relative deformation of the fiber (strain) in a unit time. Usually strain rate V_{strain} is expressed in percent per second (%/s) and is given by

$$V_{strain} = \lambda/T, \qquad (5)$$

where T is time of drawing.

In conventional commercial processes strain rate V_{strain} is high, i.e., several hundred percent per second.

In such conventional high-fiber-speed, high-drawing-speed processes the fiber is subjected to a very abrupt acceleration and rise in tension at the point where it leaves one roller to pass to the succeeding higher-speed roller. Care must be taken to ensure that the abrupt rise in tension does not break the fiber. Thus this conventional technique may be termed “impulsive drawing” because the fiber experiences a sudden “impulsive” acceleration from its initial state to its final drawn state while

traveling through the drawing machine. The "impulsive" acceleration and high tension result in frequent fiber breaks and equipment stops, high volume of waste, and prevent further fiber improvement.

Because of high fiber speed, time of drawing T is very short in most high-throughput industrial processes, i.e., less than a second for one stage drawing and about 1-3 seconds for two or three stage drawing. This results in non-equilibrium drawing where the fiber does not have enough time to be heated to ambient elevated temperature while being drawn, and the drawing occurs at high temperature gradient in the fiber cross-section. This, in turn, results in reduced drawability, reduced crystallinity, high gradient of morphology and physical properties in the cross-section, high local overstresses, and dimensionally unstable fibers with high shrinkage. This is especially typical for fibers and yarns having high denier (denier is weight in grams of 9000 meters of fiber). To provide additional time for heat setting, the existing technology requires a separate, specialized, very expensive, and energy-consuming equipment to produce dimensionally stable fibers without decrease of their tensile properties (U.S. patent 5,522,161 to Vetter (1996), U.S. patent 5,588,604 to Vetter et al. (1996) – these patents are discussed below). More often a different method for decreasing shrinkage is used in commercial processes. The fiber is subjected to restricted shrinkage while moving through a special stage which follows the last drawing stage. In doing so, the initial modulus, intermediate moduli, and tenacity are reduced.

The commercial drawing processes mentioned above do not enable one to produce polymer fibers with tensile and other physical properties close to those made by lab-scale low-fiber-speed, low-drawing-speed, long-drawing-time, and non-impulsive drawing process. This lab-scale drawing may be termed "uniform" or "equilibrium" drawing, where drawing time T is long enough to heat the fiber to the ambient temperature, while it being drawn, with low temperature gradient in the fiber cross-section. This results in uniform morphology and physical properties in the cross-section. These lab-scale experiments achieve more effective morphological transition "low-oriented -- high-oriented polymer system" and superior physical properties. For example, tenacity of lab-scale aliphatic, regular-molecular-weight, melt-spun polymer samples is higher by a factor of about 1.5-2 and initial moduli are several times higher than those for conventional commercial fibers. (As an

example, tensile properties of lab-scale polypropylene fibers can be seen in "Superdrawn Filaments of Polypropylene" by W. N. Taylor, JR. and E. S. Clark, Polym. Eng. Sci., Vol. 18, No. 6, p. 518, 1978. A comparison of these results with tensile properties of commercial polypropylene fibers is presented in Table V below). In order to overcome this large gap between the properties of lab-scale and commercial-scale polymer fibers, a new approach needs to be developed.

Moreover, within today fiber industry there is another large gap, i.e., tensile properties of low-cost, low-performance, regular-molecular-weight, melt-spun, aliphatic polymer fibers (e.g., polyethylene, polypropylene, polyester, nylon, etc.) are much lower than those of high-cost, high-performance, wholly-aromatic polymer fibers (e.g., Kevlar 49, DuPont) and ultra-high-molecular-weight, solution-spun, aliphatic polymer fibers (e.g., Spectra, Allied Signal). The great challenge for fiber science and technology is to fill this gap by producing industrially a new generation of low-cost, high-performance polymer fibers (most probably, aliphatic, regular-molecular-weight, melt-spun) with substantially improved tensile and other physical properties.. This can be done by introducing the results of the lab-scale research efforts (mentioned above) to the industry. It would be extremely attractive to achieve in the high-throughput industrial process (i.e., with take-up speed $V_{take-up}$ ranging from several hundred to several thousand meters per minute) fiber tenacity of about 1-2 GPa (12-22 gm/denier) and initial tensile modulus of about 20-100 GPa (250-1000 gm/denier) for different aliphatic polymer fibers having different theoretical values of tensile properties. In the work of Taylor and Clark mentioned above, tenacity about 1 GPa and initial modulus 22 GPa where achieved for melt-spun, regular-molecular-weight polypropylene filaments in the lab-scale experiments (see Table V below).

Any company that makes progress in this area will have a tremendous advantage in competition today and in the future. To the best of our knowledge, no significant progress in this area has been so far achieved by the American, Japanese, and European fiber industries.

A few attempts were made in the prior art to improve conventional industrial drawing methods.

A method and apparatus for incrementally drawing fibers on the industrial scale were introduced in US patent 2,372,627 to Goggin et al.(1945), in US patent 2,788, 542 to Swalm et al.(1957) and in US patents 3,978,192 (1976), 4,891,872 (1990), 4,980,957 (1991), 5,339,503 (1994), and 5,340,523 (1994), all to Sussman. The incremental drawing improves the conventional commercial drawing process by dividing it into small steps, typically 10-30, i.e., fibers are drawn on microterraced or smooth surfaces of a pair of conical rollers with canted axes.

U.S. patent 4,967,457 to Beck et al. (1990) disclosed an arrangement for stretching thermoplastic fibers. In this patent fiber moves through plurality of non-driven rollers arranged between the delivery mechanism and the stretching mechanism inside the heat chamber. Some rollers have brakes providing several successive stretching zones.

Both invented methods provide longer drawing path and drawing time T as well as lower strain rate V_{strain} in comparison with conventional methods. However, as in the conventional drawing methods the fiber, while being drawn, passes the drawing apparatuses at high speed and at the end of the drawing stage $V_{fiber2} = V_{outlet}$ (in other words, the ratio of outlet speed V_{outlet} to fiber speed V_{fiber2} is 1 to 1). If after the drawing stage the drawn fiber is conveyed to the receiving package, $V_{fiber2} = V_{outlet} = V_{take\text{-}up}$. Economical reasons force to keep speeds V_{fiber2}, V_{outlet}, and $V_{take\text{-}up}$ as high as possible, i.e., in the range from several hundred to several thousand m/min, in order to provide high throughput.

For both methods the "impulsive" acceleration, although reduced, still remains high at each drawing step or zone. In the case of high-throughput processes, the drawing is non-equilibrium, i.e., it still has short drawing time (a few seconds), which is not enough to heat the fiber (especially high-denier fiber) to the ambient temperature in the process of drawing. In the case of the incremental drawing, the fiber is drawn only between rollers and not on their surfaces while travelling through the drawing apparatus. This results in reduction of drawing time to the level which can reach about half of the residence time in the apparatus. The drawing starts and stops while the fiber moves through the drawing apparatus. Thus, the incremental drawing is not uniform and may be termed "intermittent drawing".

A technology for winding fiber in controlled loops around a conveyer device, conveying these fiber loops at a slow speed and high residence time through a heat chamber by this conveyer device, then unwinding these fiber loops, and taking up the fiber with high speed has been proposed for fiber heat setting in U.S. patent 3,426,553 to Erb (1969), U.S. Patent 3,774,384 to Richter (1973), U.S. patent 4,414,756 to Simpson et al. (1983), U.S. patent 5,522,161 to Vetter (1996), and U.S. patent 5,588,604 to Vetter et al. (1996). However, the invented method and apparatuses were not designed for and capable of fiber drawing.

BRIEF SUMMARY OF THE INVENTION

This invention relates to a method and apparatus for low-fiber-speed, low-drawing-speed, high-throughput, uniform, continuous drawing of fibers, or like flexible elements formed from natural resins, synthetic resins, or combination of both, in the form of coiled fiber loops.

The fiber is fed at an inlet speed to the drawing apparatus which includes a conveyer-drawing structure comprising a plurality of conveyer-drawing members (e.g., rotating threaded spindles or circulating endless chains) disposed about a central axis. The conveyer-drawing members have receiving ends and delivery ends spaced along the central axis and diverge from this axis in such a way that the distance between the delivery ends and the central axis is greater than the distance between the receiving ends and the central axis. The controlled fiber loops are continuously laid around the receiving ends of the moving conveyer-drawing members by a fiber winding flyer which rotates about the central axis. Thus, a layer consisting of coiled fiber loops is formed about the conveyer-drawing members. The conveyer-drawing members draw the fiber by expending the circumference of the fiber loops while conveying these loops along the central axis from the receiving ends to the delivery ends. Preferably, the fiber coil is slowly rotated about the central axis preventing the fiber loops from having permanent contact points with the conveyer-drawing members.

The coiled fiber loops, while being conveyed and drawn, are subjected to elevated temperature using heat chamber supplied with hot air, hot inert gas or superheated steam.

At the delivery ends, leading loops of the drawn fiber are successively removed by a take-off device comprising a fiber unwinding flyer which rotates about the central axis. The fiber is conveyed either to the next stage of the fiber making process or to the receiving package at high outlet speed V_{outlet} ranging from several hundred to several thousand meters per minute.

In comparison with existing industrial processes, the invented drawing process has one or more of following advantages: significantly longer drawing time T, lower strain rate V_{strain}, and lower tension in the drawing line at the same or higher fiber speeds V_{outlet} and $V_{take\text{-}up}$ and throughput. This opens the door for substantial improvement of physical properties of commercial fibers, less breaks, less equipment stops, and less waste in comparison with the prior art in industrial fiber technology.

OBJECTS OF THE INVENTION

It is an object of the present invention to provide a new method and apparatus for continuous drawing of polymer fibers that avoid the disadvantages of the prior art.

1. It is an object of the present invention to provide a new industrial method and apparatus for continuous fiber drawing which meet two requirements that are considered incompatible by the fiber industry, in particular in the area of melt-spun aliphatic polymer fibers:

(a) requirement of the fiber industry -- to have high outlet speed V_{outlet} and take-up speed $V_{take\text{-}up}$ ranging from several hundred to several thousand meters per minute to provide high throughput, and

(b) requirement of the polymer fiber science -- to provide long drawing time T and low strain rate V_{srain} which are necessary to achieve the efficient "low oriented - high oriented polymer system transition" and to produce high-performance fibers. Drawing time T needs to be long enough (i.e., ranging from several seconds to several tens of seconds) to heat the fiber in the drawing process to the ambient elevated temperature with low temperature gradient and uniform morphology and physical properties in the fiber cross-

section. Strain rate V_{strain} needs to be at least one to two orders of magnitude lower than that in the industrial processes (i.e., ranging from several %/s to several tens of %/s).

2. Another object of the present invention is to provide a new industrial method and apparatus for continuous drawing of polymer fiber (both aliphatic and wholly-aromatic) capable of substantially improving fiber tensile properties (i.e., tenacity, Young modulus, intermediate moduli, breaking elongation, etc.) approaching those obtained in laboratory experiments at low strain rate V_{strain} and long drawing time T. This will result in development of a new generation of low-cost, high-performance industrial polymer fibers (most probably melt-spun, regular-molecular-weight, aliphatic) having tenacity of about 1-2 GPa (12-22 gm/denier) and initial tensile modulus of about 20-100 GPa (250-1000 gm/denier) for different polymer fibers having different theoretical values of tensile properties.

3. Another object of the present invention is to provide a more reliable industrial process for continuous fiber drawing without abrupt, "impulsive" acceleration. This process will result in lower tension in the drawing line, less breaks, less equipment stops, and less waste than in the prior art.

4. An additional object of the present invention is to provide a new industrial method and apparatus for continuous fiber drawing which will produce dimensionally stable, low-shrinkage fibers without using expensive and energy-consuming additional equipment, while retaining improved physical properties, such as initial modulus, intermediate moduli, and tenacity, mentioned above. This may result in substantial saving in capital expenses, energy consumption, and possibility of smaller industrial space.

5. A further object of the present invention is to develop a new industrial method and apparatus for continuous fiber drawing (a) providing, in some cases, a substantial increase in the throughput in comparison with the existing industrial processes by increasing outlet speed V_{outlet} and take-up speed $V_{take-up}$ and (b) maintaining improved physical properties, such as initial modulus, intermediate moduli, tenacity, and shrinkage, mentioned above.

6. To accomplish the objects mentioned above, it is an object of the present invention to develop a new industrial method and apparatus for continuous fiber drawing which provide a ratio of outlet speed V_{outlet} to a fiber speed $(V_{fiber})_{max}$ substantially greater than 1 to 1 (i.e., preferably in the range from about 10 to 1 to about 6000 to 1), fiber speed $(V_{fiber})_{max}$ being the highest value of fiber speed V_{fiber} in the drawing process. In the prior art discussed above fiber speed $(V_{fiber})_{max}$ is fiber speed at the end of the drawing stage V_{fiber2} which equals V_{outlet}. Thus, in the prior art the ratio of V_{outlet} to $(V_{fiber})_{max}$ is 1 to 1.

Still further objects and advantages will become apparent from the consideration of the ensuing description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, closely related figures have the same number but different alphabetic suffixes.

Fig. 1A is a longitudinal view illustrating one embodiment of the present invention;

Fig. 1B shows, in schematic sectional view taken on line I-I in Fig. 1A, threaded spindles arranged in an isosceles hexagon;

Fig. 1C shows, in schematic sectional view taken on line II-II in Fig. 1A, chain wheels for rotating threaded spindles arranged in an isosceles hexagon;

Fig. 2A is a longitudinal view illustrating another embodiment of the present invention;

Fig. 2B is a fragmentary, schematic plan view illustrating the conveyer-drawing chain arrangement of the embodiment of Fig. 2A;

Figs. 2C is a fragmentary schematic views of the conveyer-drawing chains in Fig. 2A having fiber displacing members comprising guide semi-rings for controlling the fiber loop positioning;

section. Strain rate V_{strain} needs to be at least one to two orders of magnitude lower than that in the industrial processes (i.e., ranging from several %/s to several tens of %/s).

2. Another object of the present invention is to provide a new industrial method and apparatus for continuous drawing of polymer fiber (both aliphatic and wholly-aromatic) capable of substantially improving fiber tensile properties (i.e., tenacity, Young modulus, intermediate moduli, breaking elongation, etc.) approaching those obtained in laboratory experiments at low strain rate V_{strain} and long drawing time T. This will result in development of a new generation of low-cost, high-performance industrial polymer fibers (most probably melt-spun, regular-molecular-weight, aliphatic) having tenacity of about 1-2 GPa (12-22 gm/denier) and initial tensile modulus of about 20-100 GPa (250-1000 gm/denier) for different polymer fibers having different theoretical values of tensile properties.

3. Another object of the present invention is to provide a more reliable industrial process for continuous fiber drawing without abrupt, "impulsive" acceleration. This process will result in lower tension in the drawing line, less breaks, less equipment stops, and less waste than in the prior art.

4. An additional object of the present invention is to provide a new industrial method and apparatus for continuous fiber drawing which will produce dimensionally stable, low-shrinkage fibers without using expensive and energy-consuming additional equipment, while retaining improved physical properties, such as initial modulus, intermediate moduli, and tenacity, mentioned above. This may result in substantial saving in capital expenses, energy consumption, and possibility of smaller industrial space.

5. A further object of the present invention is to develop a new industrial method and apparatus for continuous fiber drawing (a) providing, in some cases, a substantial increase in the throughput in comparison with the existing industrial processes by increasing outlet speed V_{outlet} and take-up speed $V_{take\text{-}up}$ and (b) maintaining improved physical properties, such as initial modulus, intermediate moduli, tenacity, and shrinkage, mentioned above.

6. To accomplish the objects mentioned above, it is an object of the present invention to develop a new industrial method and apparatus for continuous fiber drawing which provide a ratio of outlet speed V_{outlet} to a fiber speed $(V_{fiber})_{max}$ substantially greater than 1 to 1 (i.e., preferably in the range from about 10 to 1 to about 6000 to 1), fiber speed $(V_{fiber})_{max}$ being the highest value of fiber speed V_{fiber} in the drawing process. In the prior art discussed above fiber speed $(V_{fiber})_{max}$ is fiber speed at the end of the drawing stage V_{fiber2} which equals V_{outlet}. Thus, in the prior art the ratio of V_{outlet} to $(V_{fiber})_{max}$ is 1 to 1.

Still further objects and advantages will become apparent from the consideration of the ensuing description and drawings.

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In the drawings, closely related figures have the same number but different alphabetic suffixes.

Fig. 1A is a longitudinal view illustrating one embodiment of the present invention;

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Fig. 1C shows, in schematic sectional view taken on line II-II in Fig. 1A, chain wheels for rotating threaded spindles arranged in an isosceles hexagon;

Fig. 2A is a longitudinal view illustrating another embodiment of the present invention;

Fig. 2B is a fragmentary, schematic plan view illustrating the conveyer-drawing chain arrangement of the embodiment of Fig. 2A;

Figs. 2C is a fragmentary schematic views of the conveyer-drawing chains in Fig. 2A having fiber displacing members comprising guide semi-rings for controlling the fiber loop positioning;

Fig. 2D is a fragmentary sectional view taken on line I-I in Fig. 2A showing a driving line for the conveyer-drawing chains, with some parts omitted for the sake of clarity;

Fig. 3A a longitudinal view illustrating another embodiment of the present invention;

Fig. 3B shows, in schematic sectional view taken on line I-I in Fig. 3A, pairs of chains arranged in an isosceles hexagon;

Fig. 3C is a fragmentary view of rollers mounted on the conveyer-drawing chains for embodiment of Fig. 3A;

Figs. 3D is a fragmentary view of rollers mounted on the conveyer-drawing chains for embodiment of Fig. 3A;

Fig. 3E is a fragmentary sectional view taken on line II-II in Fig. 3A showing a driving line for conveyer-drawing chains, with some parts omitted for the sake of clarity;

Fig. 3F is fragmentary view showing a driving line for the rollers supporting the fiber loops;

Fig. 3G is a fragmentary sectional view taken on line III-III in Fig. 3A, with some parts omitted for the sake of clarity;

Figs. 4 and 5 are schematic views of increase of fiber loop circumference from L_i to L_{i+1} while the loop passes distance d along the central axis that takes time Δt;.

Fig. 6 shows linear speeds of fiber points in the case of the rotation of the fiber coil about the central axis clockwise; and

Fig. 7 shows stress-strain behavior of polypropylene fibers drawn by the invented method (Tables III-V): a - sample 1, b - sample 4.

Reference Numerals in Drawings

11	heat chamber	55	shaft
12,14	support housings	56	chain wheel
13,15	bearings	58	chain
16,18	support bearings	59	shaft
20	drive shaft	60	chain wheel
20a	first inner guide channel	61	universal joint
20b	third inner guide channel	62, 62', 62"	radial arms
22	fiber winding flyer	66, 66a, 66b	chain sections
22a	outlet (of the fiber winding flyer)	68	chain wheel
22b	second inner guide channel	69	shaft
24	fiber unwinding flyer	68'	double guide chain wheel
24a	inlet (of the fiber unwinding flyer)	70, 70', 70"	radial arms
24b	fourth inner guide channel	71, 71', 71"	radial arms
25	driving gear	72	beveled gear
G	fiber	74	beveled gear
26	feed roller	76a, 76b	fiber displacing members
27	electric motor	77	guide semi-ring
28	conveying roller	78, 78', 78"	support parts
28'	roller	80	chain
30	weight	82	shaft
32	tubular support	84, 86	beveled gears
34	first sun gear	88	shaft
35	planetary carrier	90	long gear
36, 38	shafts	92	shaft
40,42	planetary pinions	96	support part
44	second sun gear	98	roller
46, 48	radial arms	98a	circumferential groove
49	radial arm	100	gear
50	guide slot	102	ball bearing
52,53	bearings	104	shaft
54	spindle	106, 106a	pins
54a, 54b	shaft portions		

DETAILED DESCRIPTION OF THE INVENTION

This invention is further illustrated by the following embodiments, which are not to be construed in any way as imposing limitations upon the scope thereof. On the contrary, it is to be clearly understood that resort may be had to various other embodiments, modifications, and equivalents thereof which, after reading the description herein, may suggest themselves to those skilled in the art without departing from the spirit of the present invention and/or the scope of the appended claims.

Figs. 1A-1C – One Embodiment.

An one embodiment of the invention for continuous drawing of fibers in form of coiled fiber loops is illustrated in Figs. 1A-1C. Fig. 1A shows a longitudinal view of an invented apparatus for the fiber drawing which has the following main parts: (a) a conveyer-drawing structure for conveying and simultaneous drawing a fiber G in the form of coiled fiber loops, (b) a feed device for feeding fiber G to the conveyer-drawing structure at an inlet speed and laying successive controlled fiber loops around the conveyer-drawing structure at the beginning of the fiber drawing, (c) a take-off device for taking continuously off the leading fiber loops from the conveyer-drawing structure at the end of the fiber drawing and conveying the drawn fiber from the fiber drawing apparatus either to the next stage of the fiber making process or to the receiving package at an outlet speed, (d) a driving mechanism for driving parts of the conveyer-drawing structure, the feed device, and the take-off device, and (e) heat chamber for heating fiber G while the fiber being conveyed and drawn. For a detailed description see below.

(a) The conveyer-drawing structure comprises six spindles 54 comprising shaft portions 54a and 54b and a thread or a spiral groove. The spindles are disposed about a central axis and have receiving ends for receiving the fiber and delivery ends for delivering the fiber and both the receiving ends and the delivery ends are spaced along the central axis. The delivery ends are spaced further from the central axis than the receiving ends. Spindles 54 are arranged in an

isosceles hexagon when viewed in cross section (Fig. 1B) and positioned at a variable divergence angle α (the same for all spindles) to the central axis.

The conveyer-drawing structure comprises support housings 12 and 14, support bearings 16 and 18, bearings 13 and 15, bearings 52 and 53, a drive shaft 20, a tubular support 32, and radial arms 46, 48, 62, 62', and 62" (six of each arm). The radial arms are arranged in an isosceles hexagon when viewed in cross section. Bearings 16 and 18 are mounted in housings 14 and 12 respectively and support shaft 20. Bearings 13 and 15 are mounted in tubular support 32. Shaft 20 supports tubular support 32 (by means of bearings 13 and 15), and support 32 supports radial arms 46, 48, 62, 62', and 62". Arms 48 support bearings 52. Bearings 52 can be moved along and secured in slots 50 in arms 48, angle α of spindles 54 being changed. Arms 62 support bearings 53. Bearings 53 and 52 support shaft portions 54a and 54b of spindles 54 respectively. Arms 62' and 62" support spindles 54 to prevent sagging.

The conveyer-drawing structure comprises a stabilizing mechanism which prevents rotation of the conveyer-drawing structure (to put it more precisely, its parts supported by tubular support 32) about the central axis. The stabilizing mechanism is located at the receiving ends of spindles 54. It comprises a planetary carrier 35, shafts 36 and 38, a pair of planetary pinions 40, a pair of planetary pinions 42, a first sun gear 34, and a second sun gear 44.

Planetary carrier 35 is secured to shaft 20, shafts 36 and 38 are mounted on carrier 35 for rotation, planetary pinions 40 are secured to shaft 36, planetary pinions 42 are secured to shaft 38, first sun gear 34 is secured to tubular support 32, and second sun gear 44 is secured to support housing 14.

(b) The feed device comprises a pair of driven feed rollers 26, a fiber winding flyer 22, an outlet 22a, a first inner guide channel 20a, a second inner guide channel 22b, a polytetrafluoroethylene tube (not shown), carrier 35, and shaft 20 (carrier 35 and shaft 20 are also parts of the conveyer-drawing structure, see above). Flyer 22 is secured to carrier 35 at the receiving ends of spindles 54. Flyer 22 has outlet 22a at its free end and second guide channel 22b communicating with first

guide channel 20a passing through the end portion of shaft 20 and planetary carrier 35. The polytetrafluoroethylene tube (not shown) is inserted into channels 20a and 22b up to outlet 22a, the fiber passing through the channels with very little friction.

(c) The take-off device comprises a pair of driven conveying rollers 28, a roller 28', a weight 30, an fiber unwinding flyer 24, an inlet 24a, a third inner guide channel 20b, a fourth inner guide channel 24b, a polytetrafluoroethylene tube (not shown), and shaft 20 (it is also a part of the conveyer-drawing structure and the feed device, see above). Flyer 24 is secured to shaft 20 at the delivery ends of spindles 54. Flyer 24 has inlet 24a at its free end and fourth guide channel 24b communicating with third guide channel 20b passing through the other end portion of shaft 20. Roller 28' supports weight 30. The polytetrafluoroethylene tube (not shown) is inserted into channels 20b and 24b up to inlet 24a, the fiber passing through the channels with very little friction.

(d) The driving mechanism comprises an electric motor 27, a driving gear 25, shaft 20 (it is also a part of the conveyer-drawing structure, the feed device, and the take-off device, see above), six chain wheels 56, a chain wheel 60, a chain 58, universal joints 61, shafts 55, a shaft 59, and an adjustable transmission (not shown). Gear 25 is secured to shaft 20. Chain wheels 56 are secured to shafts 55 mounted in arms 46 for rotation. Chain wheel 60 is mounted on shaft 59 for rotation and connected by the adjustable transmission (not shown) to shaft 20 (Fig. 1C). Shaft 59 is secured to arm 46. Chain 58 passes over wheels 56 and wheel 60. Universal joints 61 are mounted on the other ends of shafts 55 and connected to shaft portions 54a of spindles 54 (Figs. 1A and 1C).

(e) The heat chamber 11 envelopes the conveyer-drawing structure (besides support housings 12 and 14 and bearings 16 and 18), the winding and unwinding flyers, and the driving mechanism besides motor 27 and gear 25. It is supplied with hot air, hot inert gas, or superheated steam.

Figs. 1A-1C – Operation.

Electric motor 27 rotates gear 25 and hence rotates shaft 20 in bearings 16, 18, 13 and 15. Shaft 20 rotates carrier 35 with flyer 22, flyer 24, shafts 36 and 38, and pinions 40 and 42 about the central axis. Pinions 40 and 42 roll on sun gears 34 and 44 preventing support 32 from turning about shaft 20 and the central axis. Thus the parts of the conveyer-drawing structure supported by tubular support 32 are prevented from rotation about the central axis.

Spindles 54 are rotated by means of electric motor 27, gear 25, shaft 20, the adjustable transmission (not shown), wheel 60, chain 58, wheels 56, shafts 55, and universal joints 61. Shaft portions 54a and 54b of spindles 54 rotate in bearings 53 and 52, respectively.

Fiber G comes to feed rollers 26 at an inlet speed either from a previous stage of the fiber making process (e.g., spinning, previous stage of drawing, etc.) or from a feeder package. The fiber passes through channels 20a and 22b and comes out of outlet 22a. Flyer 22 rotates with shaft 20 and carrier 35 and lays successive controlled fiber loops about the receiving ends of rotating spindles 54. Spindles 54 are rotated in such a direction that the newly laid fiber loops travel to the left along the central axis, as viewed in Fig. 1A, freeing room for the next laid fiber loop. A layer of the coiled fiber loops is formed around spindles 54. The spindle thread or spiral groove serves as a fiber displacing member providing the fiber loop conveying along the central axis and the fiber drawing.

Both flyers 22 and 24 make one revolution while spindles 54 make one revolution. As this takes place, each fiber loop travels along the central axis one pitch of the fiber coil. Simultaneously the fiber coil is slowly rotated about the central axis, and each point of the fiber loop passes along the loop circumference a distance equal to a spindle circumference (measured at inner diameter of the thread or spiral groove). The loops increase their circumference with each spindle revolution, the fiber gradually being drawn by rotating spindles 54 at the heat chamber temperature. The leading fiber loops are continuously unwound by flyer 24 at the delivery ends of spindles 54. The corresponding length of the fiber is conveyed through inlet 24a and guide

channels 24b and 20b by the conveying rollers 28 and roller 28'. The fiber is conveyed either to the next stage of the fiber making process or, through a winder (not shown), to the receiving package (not shown). The fiber does not have permanent contact points with the spindles. This provides the uniformity of the dimensions and physical properties of the drawn fiber.

For the invented method and apparatus, the fiber draw ratio λ equals the ratio of the loop circumference at the delivery ends to that at the receiving ends. It can be changed by moving bearings 52 along guide slots 50 in arms 48 and securing them there, angle α of spindles 54 being changed. This results in changing the loop circumference at the receiving ends. Heights of arms 62' and 62" supporting spindles 54 are adjusted when angle α is changed. The fiber, while being fed to and taken off the spindles, is under tension and cannot shrink because feed rollers 26 and conveying rollers 28 with roller 28' and weight 30 carry out tension control along with additional tension control devices (not shown) placed before and after the whole apparatus.

Figs. 2A-2D -- Another Embodiment

The embodiment illustrated in Figs. 2A-2D corresponds to the embodiment of Figs. 1A-1C and corresponding parts have the same reference numbers. In the conveyer-drawing structure spindles 54 (Fig. 1A) are replaced with the same number (six) of circulating chain members arranged in an isosceles hexagon when viewed in the cross section. Each chain member is subdivided into three separate endless circulating chain sections 66, 66a, and 66b which pass over chain wheels 68 and double guide chain wheels 68' (Figs. 2A and 2B).

All chains have a plurality of displacing members 76a and 76b. Each chain link has either displacing member 76a or displacing member 76b (Fig. 2C). Each displacing member comprises a guide semi-ring 77 for fiber support. For the sake of clarity, we do not illustrate the displacing members over all the chain sections in Fig. 2A. Wheels 68 are mounted on radial arms 48 and 70, and wheels 68' are mounted on radial arms 70' and 70" for rotation. Arms 70 support shafts 69 which carry wheels 68 and beveled gears 74 (Fig. 2D). Gears 74 are engaged with beveled gears 72 carried by shafts 55 which is mounted on arm 46 for rotation (Figs. 2A and 2D). Wheels 68

can be moved along and secured in guide slots 50 of arms 48, divergence angle α between the chain sections and the central axis being changed. Heights of arms 70' and 70" are adjustable, and the arms can be moved and secured along support 32. Angle α is the same for each chain section 66, 66a, or 66b, but can be either different or the same for different sections. The chains slide along support parts 78, 78', and 78" to prevent chain sagging under drawing forces. These parts are stationary, supported by arms 48, 70', 70", and 70, and their inclination angle with respect to the central axis can be changed along with the change of angle α for each chain section.

As shown in Figs. 2A and 2B, sections 66, 66a, and 66b pass over double guide chain wheels 68' so that the delivery end of each chain section overlaps with the receiving end of the next chain section. Since adjacent receiving and delivery ends are circumferentially spaced, they support different portions of the fiber loops moved by the circulating chains along the central axis.

This changes contact points between the fiber and the fiber displacing members thus resulting in better uniformity of dimensions and physical properties of the drawn fiber.

Figs. 2A-2E -- Operation

The chains are driven by means of electric motor 27, gear 25, shaft 20, the adjustable transmission (not shown), wheel 60, chain 58, wheels 56, gears 72 and 74, and wheels 68 and 68' (Figs. 2A, 2B, and 2D). Both flyers 22 and 24 make one revolution while chains 66, 66a, and 66b move one chain pitch. Flyer 22 lays controlled fiber loops about the receiving ends of chains 66 placing each loop in contact with guide semi-rings 77 of displacing members 76a and 76b (Fig. 2C) which facilitate the fiber loop conveying along the central axis and the fiber drawing. The rest of the operation is the same as in the case of the embodiment of Fig. 1A.

Figs. 3A - 3G -- Another Embodiment

The embodiment illustrated in Figs. 3A-3G corresponds to the embodiments of Fig. 2A-2D and corresponding parts have the same reference numbers. In the conveyer-drawing structure, the six

chains having sections 66, 66a, and 66b (Fig. 2A) are replaced by six pairs of parallel circulating endless chains 80 which are not subdivided in three separate section each as in the embodiment of Figs. 2A. These six chain pairs are arranged in an isosceles hexagon when viewed in cross section (Fig. 3B). They pass over wheels 68 at both the receiving and delivery ends. The chains slide along support parts 96 to prevent chain sagging under drawing forces. These parts are stationary, supported by radial arms 71, 71', 71", and 49, and their inclination angle with respect to the central axis can be changed along with the change of divergence angles α of chains 80.

Displacing members are mounted on the parallel chains. They comprise rollers 98 having circular circumferential grooves 98a, pins 106 and 106a, shafts 104, and ball bearings 102 (Figs. 3C and 3D). Each pair of the parallel chains is joined by pins 106 and 106a. Each pair of chain links (one link from each chain) is joined by either by two pins 106 or two pins 106a. Lateral parts of the chains are modified to support the pins. Each pair of pins 106 and 106a supports a shaft 104 which carries roller 98 with ball bearing 102. The axes of shafts 104 are adjusted nearly parallel to the central axis of the drawing apparatus while the fiber draw ratio is changed by varying divergence angle α of chains 80. To achieve this, the angle between shafts 104 and the chain is adjusted for each roller 98 by rotating shafts 104 around pins 106 and 106a. Other pins 106 and 106a are moved along and secured to the side portions of the chains (Fig. 3C). Gears 100 are attached to each side of rollers 98. For the sake of clarity we did not illustrate rollers 98 over all chains 80 in Fig. 3A.

Each shaft 82 mounted in arm 70 carries two wheels 68, a beveled gear 84, beveled gear 74, and supports one end of a shaft 88 (Figs. 3E and 3F). Beveled gears 84 are engaged with beveled gears 86 fastened to long gears 90. Gears 86 and 90 are mounted on shafts 88 (Fig. 3F). Gears 90 are engaged with gears 100 of rollers 98 (Figs. 3C-3F). The other end of shaft 88 is supported by shaft 92 (Fig. 3G). Shafts 92 are supported by arms 49 and can be moved along and secured in guide slots 50. As this takes place, shafts 88 turn around shafts 82, and gears 86 roll around gears 84, both gears remaining engaged. Two wheels 68 are mounted on each shaft 92 (Fig. 3G).

Figs. 3A - 3G -- Operation

Chains 80 are driven by means of electric motor 27, gear 25, shaft 20, the adjustable transmission (not shown), wheel 60, chain 58, wheels 56, gears 72 and 74, and wheels 68 (Figs. 3A and 3E). At the same time gears 84 rotate gears 86 and long gears 90 (Figs. 3E and 3F). Gears 90 rotate gears 100 and rollers 98 while rollers 98 are moved by chains 80 from the receiving ends, along gears 90, to the delivery ends. Flyers 22 and 24 make one revolution while chains 80 move one chain pitch. Flyer 22 lays controlled fiber loops about the receiving ends of chains 80 placing each loop in grooves 98a of rollers 98 (Fig. 3C and 3D) and forming the layer of coiled fiber loops supported by the rollers. Rollers 98, as a part of the displacing members, facilitate the fiber loop conveying along the central axis and the fiber drawing. As the fiber loops travel to the left along the central axis, as viewed in Fig. 3A, the fiber coil is rotated about the central axis by rollers 98. This changes contact points between the fiber and the rollers thus resulting in a better uniformity of dimensions and physical properties of the drawn fiber. Rotation speed of rollers 98 and the fiber coil is adjustable. The rest of the operation is the same as in the case of embodiment of Fig. 2A.

The apparatus can be used with rollers 98 not being rotated by the driving mechanism. In this instance, the coiled fiber loops, supported by free-to-rotate rollers, are not rotated about the central axis. In some cases this is sufficient to produce the drawn fiber having uniformity of the dimensions and physical properties along the fiber axis.

Calculations

As discussed above, in contrast to the prior art, the invented continuous drawing method provides that fiber linear speed $(V_{fiber})_{max}$ in the drawing process is substantially lower than outlet speed V_{outlet} (the ratio of V_{outlet} to $(V_{fiber})_{max}$ is greater than 1 to 1). At the same time, strain rate V_{strain} is substantially lower and drawing time T is substantially longer than those in the existing industrial processes without reducing, and in some cases even increasing, the throughput. The following calculations support these statements.

The speed of conveying the fiber loops along the central axis V_{loop} is given by

$$V_{loop} = d/\Delta t \quad \text{and} \tag{6}$$

$$\Delta t = d/ V_{loop}, \tag{7}$$

where d is the distance between adjacent loops in the fiber coil along the central axis, i.e., a pitch of the fiber coil and

Δt - time needed for the fiber loop to pass distance d.

According to the mass conservation rule, in a continuous fiber making process equal fiber mass should pass through any cross-sectional plane (plane perpendicular to the central axis) in a unit time both inside and outside of the apparatus. For the fiber having the same draw ratio λ, the fiber mass is in proportion to the fiber length.

Inside of the apparatus, at the delivery ends a fiber length L, which is the circumference of the leading fiber loop at the delivery ends, passes cross-sectional plane for time Δt (see above). Outside the apparatus, while the fiber being conveyed either to the next stage of the fiber making process or to the receiving package, the same length L of the straightened fiber (having the same λ) should pass cross-sectional plane for the same time Δt. Thus, outlet speed V_{outlet} is given by

$$V_{outlet} = L/\Delta t, \tag{8}$$

Thus, equations (7) and (8) lead to a ratio A

$$A = V_{outlet}/V_{loop} = L/d. \tag{9}$$

Figs. 4 and 5 show, in schematic view, the increase of fiber loop circumference from L_i to L_{i+1} while the loop passes distance d along the central axis that takes time Δt. In the cases of the

embodiments of Figs. 1A-3A, the fiber loops are isosceles hexagons and consist of six equal fiber sections (Fig. 5). Each section is drawn between two adjacent conveyer-drawing members. As an example, section KP becomes section FW. The length increase is FH + QW (lines KH and PQ are perpendicular to line FW; FH = QW). Each point of section KP is drawn with at linear speed along the fiber axis V_{fiber} which is different for different points of the section. Points K and P have the highest speed V_{fiber} in the drawing process designated as V_{fiberK} and V_{fiberP}. The middle point of section KP has speed $V_{fiber} = 0$ (for the case where the coiled fiber loops are not rotated about the central axis). Thus the highest value of fiber speed V_{fiber} in the drawing process $(V_{fiber})_{max}$ is given by

$$(V_{fiber})_{max} = V_{fiberK} = V_{fiberP} = QW/\Delta t = (PW\cdot\cos\varphi_1)/\Delta t \qquad (10)$$

From isosceles triangle POK (Fig. 5) we get

$$\varphi_1 = (180 - \varphi)/2 \qquad (11)$$

In the case where n conveyer-drawing members are arranged in an isosceles polygon, angle φ is given by

$$\varphi = 360/n, \qquad (12)$$

From equations (11) and (12) we get

$$\varphi_1 = (180 - 360/n)/2 = 90\cdot(1-2/n) \qquad (13)$$

From equations (10) and (13) we get

$$(V_{fiber})_{max} = PW\cdot\cos[90\cdot(1-2/n)]\cdot 1/\Delta t \qquad (14)$$

From Fig. 4 we get

$$PW = d \cdot tg\,\alpha \quad \text{and} \tag{15}$$

$$(V_{fiber})_{max} = d \cdot tg\,\alpha \cdot \cos[90 \cdot (1-2/n)] \cdot 1/\Delta t \tag{16}$$

From equations (6) and (16) we get

$$(V_{fiber})_{max} = V_{loop} \cdot tg\,\alpha \cdot \cos[90 \cdot (1-2/n)] \tag{17}$$

From equations (9) and (17) we get

$$(V_{fiber})_{max} = V_{outlet} \cdot d \cdot 1/L \cdot tg\,\alpha \cdot \cos[90 \cdot (1-2/n)] \tag{18}$$

Thus, fiber speed $(V_{fiber})_{max}$ is constant during the drawing at given V_{outlet}, d, L, n, and α.

Equation (18) leads to a ratio B

$$B = V_{outlet}/(V_{fiber})_{max} = L/\{d \cdot tg\,\alpha \cdot \cos[90 \cdot (1-2/n)]\} \tag{19}$$

In the case of rotation of the coiled fiber loops about the central axis (like in the embodiments of Fig. 1A and Fig. 3A), each point of the fiber loop rotates with a linear speed $V_{rotation}$ (Fig. 6; speed $V_{rotation}$ is perpendicular to a radius of rotation, e.g., OP or OK). Each point of the fiber loop in the process of rotation of the loop about the central axis passes a distance L_{fiber} while the loop as a whole passes distance d along the central axis for time Δt. Distance L_{fiber} is given by

$$L_{fiber} = V_{rotation} \cdot \Delta t \tag{20}$$

From equations (8) and (20) we get

$$L_{fiber} = (V_{rotation}/V_{outlet})\cdot L \tag{21}$$

During the drawing, while the fiber loop passes from the receiving to delivery ends, each point of the fiber loop in the process of the rotation of the loop about the central axis passes total distance designated as L_{total} which is given by

$$L_{total} = L_{fiber}\cdot(N - N') = (V_{rotation}/V_{outlet})\cdot L\cdot(N - N'), \tag{22}$$

where N is a number of the fiber loops in the heat chamber which is given by

$$N = M/d, \tag{23}$$

where M is a length of the fiber coil along the central axis, and

N' is a number of loops with an average circumference $L_{average}$ which have the total circumference equals L_{total} and is given by

$$N' = L_{total}/ L_{average}, \tag{24}$$

where the average circumference $L_{average}$ of the fiber loops in the heat chamber is given by

$$L_{average} = (L + L')/2, \tag{25}$$

where L' is the circumference of the first fiber loop at the receiving ends.

The draw ratio λ is given by

$$\lambda = L/L' \quad \text{and} \tag{26}$$

$$L_{average} = (L + L/\lambda)/2 \tag{27}$$

From equations (22) and (24) we get

$$N' = N/(L_{average}/L_{fiber} + 1) \quad (28)$$

One can see that the larger the ratio $L_{average}/L_{fiber}$, the smaller N' in comparison with N.

Thus, time of drawing T, which is time needed for each fiber point to pass from the receiving ends to the delivery ends, is given by

$$T = (M - N'\cdot d)/ V_{loop} = [A\cdot(M - N'\cdot d)]/ V_{outlet} =$$

$$= [L\cdot(M - N'\cdot d)]/ (V_{outlett}\cdot d) \quad (29)$$

In the case of the rotation of the fiber coil about the central axis in clockwise direction (Fig. 6), the linear speeds of fiber points K and P along the fiber axis are $(V_{fiberK})_{rotation}$ and $(V_{fiberP})_{rotation}$ respectively, and they are given by

for point K -- $(V_{fiberK})_{rotation} = V_{rotation}\cdot\sin\varphi_1 - V_{fiberK} =$

$$= V_{rotation}\cdot\sin[90\cdot(1\text{-}2/n)] - V_{fiberK} \quad \text{and} \quad (30)$$

for point P -- $(V_{fiberP})_{rotation} = V_{rotation}\cdot\sin[90\cdot(1\text{-}2/n)] + V_{fiberP} =$

$$= V_{rotation}\cdot\sin[90\cdot(1\text{-}2/n)] + V_{fiberP} \quad (31)$$

The fiber linear speed for point P is higher than that for point K. Thus, in the case of the fiber coil rotation fiber speed $(V_{fiber})_{max}$ is given by

$$(V_{fiber})_{max} = (V_{fiberP})_{rotation} = V_{rotation}\cdot\sin[90\cdot(1\text{-}2/n)] + V_{fiberP} \quad (32)$$

Example 1.

Table I gives the results of calculations for the case: $L = 5500$ mm, $V_{outlet} = V_{take\text{-}up} = 3000$ m/min (the fiber is conveyed to the receiving package after the drawing stage), $n = 6$, $\lambda = 5$ to 1 (400 %), and d, M and A are variable. The coiled fiber loops are not rotated about the central axis. Take-up speed of 3000 m/min is typical take-up speed for the commercial process for multifilaments and yarns.

Example 2.

Table II gives results of calculations for the case: $L = 2000$ mm, $V_{outlet} = V_{take\text{-}up} = 500$ m/min (the fiber is conveyed to the receiving package after the drawing stage), $n = 6$, $\lambda = 5$ to 1 (400 %), and d, M and A are variable. The coiled fiber loops are not rotated about the central axis. Take-up speed of 500 m/min is typical take-up speed for the commercial process for tape yarns and monofilaments.

Example 3.

In this example the coiled fiber loops are rotated about the central axis like in the embodiments of Figs. 1A and 3A. In this case, time of drawing T, fiber linear speed $(V_{fiber})_{max}$, and strain rate V_{strain} need to be corrected. They are calculated for the case No. 8, Table I for the embodiment of Fig. 1A. For this embodiment, as discussed above, L_{fiber} is always equal the spindle circumference (measured at inner diameter of the thread) and is given by

$$L_{fiber} = \pi \cdot D_{spindle}, \qquad (33)$$

where $D_{spindle}$ is an inner diameter of the thread of the spindle.

For the size of $D_{spindle} = 40$ mm, as an example, the calculated parameters according to equations(5)-(33) are as follows:

$L_{fiber} = 125.6$ mm,

$V_{rotation} = 68.5$ m/min

Table I. Results of Calculations for Example 1.

	Length of the fiber coil along the central axis M, mm	Pitch of the fiber coil d, mm	A = $V_{outlet}/V_{loop} = V_{take-up}/V_{loop}$ = L/d	Fiber loop speed V_{loop} = 3000/A, m/min	Time of drawing T = M/V_{loop}, s *)	Number of loops in the heat chamber, N=M/d	Linear fiber speed in the drawing process $(V_{fiber})_{max}$, m/min *)	B = $V_{outlet}/(V_{fiber})_{max} = V_{take-up}/(V_{fiber})_{max}$ = 3000/ $(V_{fiber})_{max}$, m/min	Strain rate V_{stram} = λ/T= 400/T, %/s *)	Divergence angle α for draw ratio λ 5 to 1, deg. **)
1	500	5	1100	2.7	11.1	100	2.0	1500	36	55.7
2	500	7.5	733	4.1	7.3	67	3.0	1000	54.8	55.7
3	500	10	550	5.4	5.6	50	4.0	750	72	55.7
4	1000	5	1100	2.7	22.2	200	1.0	3000	18	36.3
5	1000	7.5	733	4.1	14.6	134	1.5	2000	27.4	36.3
6	1000	10	550	5.4	11.1	100	2.0	1500	36	36.3
7	2000	5	1100	2.7	44.4	400	0.5	6000	9	20.1
8	2000	7.5	733	4.1	29.2	268	0.75	4000	13.7	20.1
9	2000	10	550	5.4	22.2	200	1.0	3000	18	20.1
10	3000	5	1100	2.7	66.6	600	0.34	8956	6	13.7
11	3000	7.5	733	4.1	43.8	400	0.5	6000	9	13.7
12	3000	10	550	5.4	33.3	300	0.65	4512	12	13.7

*) In case of the fiber coil rotation about the central axis, T, V_{strain}, and $(V_{fiber})_{max}$ need to be corrected according to equations (29), (5), and (32) respectively (see Example 3).

**) In case of the embodiment with the conveyer-drawing chains consisting of several sections (Fig. 2A), all chain sections have the same divergence angle α.

$L_{average}$ = 3300 mm for λ = 5 to 1 (400%),

N' = 9.8,

T = 28.3 s (compare with 29.2 s in Table I).

$(V_{fiber})_{max} = 0.75 + 68.5 = 69.25$ m/min

$V_{output}/(V_{fiber})_{max} = 43.3$

$V_{strain} = 14.1$ %/s

Thus, in the cases examined in Examples 1-3, fiber linear speed $(V_{fiber})_{max}$ is low, i.e., 0.1- 4 m/min for Examples 1 and 2 and 69 m/min for Example 3, time of drawing T can reach tens of seconds, strain rate V_{strain} is low, i.e., 6-70 %/s, and the ratio of V_{outlet} to $(V_{fiber})_{max}$ is

Table II. Results of Calculations for Example 2.

	Length of the fiber coil along the central axis M, mm	Pitch of the fiber coil d, mm	A = V_{outlet}/V_{loop} = $V_{take\text{-}up}/V_{loop}$ = L/d	Fiber loop speed V_{loop} = 3000/A, m/min	Time of drawing T = M/V_{loop}, s *)	Number of loops in the heat chamber, N=M/d	Linear fiber speed in the drawing process $(V_{fiber})_{max}$, m/min *)	B = $V_{outlet}/(V_{fiber})_{max}$ = $V_{take\text{-}up}/(V_{fiber})_{max}$ = 3000/$(V_{fiber})_{max}$, m/min	Strain rate V_{strain} = λ/T= 400/T, %/s *)	Divergence angle α for draw ratio λ 5 to 1, deg. **)
1	500	5	400	1.25	24	100	0.34	1492	16.7	28.1
2	500	7.5	267	1.87	16	67	0.50	1000	25	28.1
3	500	10	200	2.5	12	50	0.67	746	33.3	28.1
4	1000	5	400	1.25	48	200	0.17	3030	8.3	14.9
5	1000	7.5	267	1.87	32	134	0.25	2000	12.5	14.9
6	1000	10	200	2.5	24	100	0.34	1492	16.7	14.9
7	1500	5	400	1.25	72	300	0.11	4546	5.6	10.1
8	1500	7.5	267	1.87	48	200	0.17	3030	8.3	10.1
9	1500	10	200	2.5	36	150	0.22	2222	11.1	10.1

*) In case of the fiber coil rotation about the central axis, T, V_{strain}, and $(V_{fiber})_{max}$ need to be corrected according to equations (29), (5), and (32) respectively (see Example 3).

**) In case of the embodiment with the conveyer-drawing chains consisting of several sections (Fig. 2A), all chain sections have the same divergence angle α.

substantially greater than 1 to 1, i.e., varying from the ratio 43 to 1 to the ratio 6000 to 1 (the fiber drawing apparatus can be constructed and arranged to provide the ratio, if necessary, lower than 43 to 1 and greater than 6000 to 1). In the case of conventional commercial drawing process having the same λ = 400% and $(V_{fiber})_{max} = V_{fiber2} = V_{outlet} = V_{take\text{-}up}$ = 3000 m/min., time of drawing T is about 1 second, and V_{strain} is substantially higher, i.e., about 400 %/s.

In the invented method, time of drawing T in some cases is so long that it can be decreased by a factor of 1.5-2 remaining sufficiently long (20-40 sec) to perform uniform hot drawing of even high denier fibers. Thus, speeds V_{loop}, V_{outlet}, and $V_{take\text{-}up}$ can be also increased in these cases at least by a factor of 1.5-2, resulting in the 1.5-2-fold increase and more of the throughput . Thus, the take-up speed can be 4500-6000 m/min and more.

Example 4. Drawing of Polypropylene Fibers.

The first version of a prototype of the drawing apparatus was build. The drawing apparatus comprises two endless chains as the conveyer-drawing members, non-driven, free-to-rotate rollers as the guide members of the displacing elements, and a heat chamber supplied with hot air. The feed and take-off devices or mechanisms were not built at this first stage. However, this type of mechanisms was proved to be feasible and was successively used in the industrial processes for heat setting of polymer fibers discussed above. The heat chamber of this unit was 1000 mm. long.

Polypropylene commercial resin from Amoco Chemical Co. (grade 10-6345) was used. The resin had the following parameters: Melt Flow Rate - 3.1 gm/10 min., M_w = 370,000, and MWD = 5.6. It was extruded at 220°C through the 0.5 mm spinneret orifice and quenched in a water bath at room temperature. Wide-angle X-ray diffraction pattern revealed that the as-spun fiber produced was unoriented and low-crystalline.

The drawing process was performed in two separate stages using the drawing apparatus twice, at different temperatures. These two stages of drawing represent two different drawing mechanisms occurring on the molecular level. The initial drawing stage converts the undrawn spherulitic as-spun fiber into a fiber with fibrillar structure developed through a necking-down mechanism. The first stage can be rapid. It is followed by the second drawing stage which is named superdraw. The second drawing stage orients the newly formed fibrillar structure. This stage needs to be much slower to produce polymer fibers with improved physical properties approaching those achieved in lab-scale experiments mentioned above.(V. A. Marikhin and L. P. Myasnikova, "Nadmolekulyarnaya Struktura Polymerov", St. Petersburg, Russia, Khimia (1977), Progr. Colloid Polym. Sci., 92, 39-51 (1993), W. N. Taylor and E. S. Clark, Polym. Eng. Sci., 18 , 518-526 (1978)). The rapid first stage can be performed effectively by both conventional and the invented drawing methods. The slower second stage needs to be performed by the invented method and apparatus.

The heat chamber was preheated to given drawing temperatures (see Tables III and IV below) with the chains at rest. The front door of the chamber was open, loops of polypropylene (PP) fibers were placed about the receiving ends of the chains and supported by the roller grooves inside of the heat chamber, the chamber door was closed, and temperature was raised to given temperatures for 30-300 seconds (see Tables III and IV). Then the driving electrical motor was turned on, and the chains started to move conveying the fiber loops through the heat chamber and simultaneously drawing the fiber. When the fiber reached the delivery ends of the chains, the equipment was stopped, the chamber door was opened, and the drawn fiber was cooled down for 20-300 seconds (see Tables III and IV) before being removed.

Tensile properties were measured by an Instron tensile-testing machine. The breaking length was 30 mm., and the lower clamp speed was 50 mm/min. Results can be seen in Table V along with results on shrinkage. Each result is an average of three tests. Results for conventional commercial PP fibers are presented for comparison.

Thus the results of the first experiments confirm that the invented method is capable of producing industrial polymer fibers with superior physical properties in comparison with the conventional industrial processes and approaching those generated in the lab-scale experiments. Our results are very close to laboratory results reported in paper of Taylor and Clark (see Table V) for regular-molecular-weight polypropylene fibers, i.e., our samples have tenacity 0.9-1.2 GPa (11-14.5 gpd) and tensile initial modulus 17.7-20.5 GPa (214-248 gpd).

As presented in Tale V, for polypropylene fibers tenacity is increased by a factor of 1.2-3.0, initial modulus is increased by a factor of 4.8-8.5, and breaking elongation is decreased by a factor of 1.5-4 in comparison with conventional industrial processes. This is accompanied by excellent dimensional stability, i.e., hot air shrinkage is 0-3 % at 132 °C.

As an example, stress-strain behavior of the samples 1 and 4 from Tables III-V is presented in FIG. 7. In contrast to many commercial PP fibers, the stress-strain curves do not have the yielding part or plateau, that indicates high intermediate moduli and, probably, low creep.

Table III. Drawing Conditions for Polypropylene Fibers, First Stage of Drawing

	t_1, s	T_1, °C	t_2, s	T_2, °C	t_3, s	λ_1	$(V_{fiber})_{max1}$, m/min	$V_{strain1}$, %/s
1	120	80	52	80	20	7.6	0.24	12.7
2	100	80	50	80	20	7.1	0.25	12.2
3	130	80	56	80	20	7.7	0.22	12.0
4	120	80	52	80	20	7.1	0.24	11.7
5	110	80	58	80	20	7.7	0.22	11.5
6	120	80	54	80	20	7.7	0.23	12.4

T_1- beginning drawing temperature of the first drawing stage
T_2 - final drawing temperature of the first drawing stage
λ_1 - draw ratio for the first drawing stage
t_1 - time of heating the chamber, with the fiber and chains at rest, to temperature T_1
t_2 - time of drawing the fiber
t_3 - time of cooling drawn fiber with the fiber and chains at rest and the chamber door open
$(V_{fiber})_{max1}$ - the highest value of fiber speed V_{fiber} at the first drawing stage
$V_{strain1}$ - fiber strain rate at the first drawing stage

Table IV. Drawing Conditions for Polypropylene Fibers, Second Stage of Drawing

	t_4, s	T_3, °C	t_5, s	T_4, °C	t_6, s	λ_2	$(V_{fiber})_{max2}$, m/min	$V_{strain2}$, %/s	$\lambda = \lambda_1 \times \lambda_2$
1	240	140	168	140	30	2.6	0.03	0.9	19.8
2	300	140	160	140	30	2.6	0.03	1.0	18.5
3	280	155	185	155	30	2.7	0.02	1.1	20.8
4	30	135	30	142	300	2.3	0.15	4.3	16.3
5	40	130	80	139	240	2.4	0.58	1.8	18.5
6	50	133	90	143	240	2.5	0.50	1.7	19.2

T_3- beginning drawing temperature of the second drawing stage
T_4- final drawing temperature of the second drawing stage
λ_2 - draw ratio for the second drawing stage
t_4 - time of heating the chamber, with the fiber and chains at rest, to temperature T_3
t_5 - time of drawing the fiber in the temperature range from T_3 to T_4
t_6 - time of cooling drawn fiber with the fiber and chains at rest the chamber door open
$(V_{fiber})_{max2}$ - the highest value of fiber speed V_{fiber} at the second drawing stage
$V_{strain2}$ - fiber strain rate at the second drawing stage
λ - total draw ratio

Table V. Physical Properties of Polypropylene Fibers

	Tenacity, GPa (gm/denier)	Tensile Initial Modulus, GPa (gm/denier)	Breaking Elongation, %	Hot Air Shrinkage at 132 °C, %
1	1.2 (14.5)	19.2 (232)	8.0	0
2	0.9 (10.9)	19.1 (231)	6.6	0
3	0.9 (10.9)	20.5 (248)	7.6	0
4	1.1 (13.3)	17.8 (215)	10.2	3
5	0.9 (10.9)	17.7 (214)	7.6	2
6	1.05 (12.7)	18.9 (229)	9.7	2
Commercial PP fibers (Herculon, Marvess)	0.4-0.7*) (5-9)	2.4-3.7*) (29-45)	15-30*)	2-10**)
Lab-scale PP fibers***)	0.93 (11.2)	22 (266)	6.2	-

*) Encyclopedia Britannica 2001 (http://www.britannica.com/eb/article?eu=126288), "Properties and Applications of Prominent Man-Made Fibres".

**) Low values of the shrinkage could be a result of fiber relaxation or heat setting after the drawing discussed above.

***) W. N. Taylor and E. S. Clark, Polym. Eng. Sci., 18 , 518-526 (1978). PP resin: M_w = 277,000, MWD = 10. Heating medium - silicon oil. First drawing stage: initial length - 100 mm, $V_{fiber1} = 1$ m/min, $V_{strain1} = 16.7$ %/s, $T_2 = 130$ °C. Second drawing stage: $V_{fiber2} = 0.001$ m/min, $V_{strain2} = 0.07$ %/s, $T_4 = 130$ °C, total $\lambda = 25$.

Advantages.

From the descriptions, calculations, and results of experiments given above, one or more of following advantages of the invented drawing method and apparatus in comparison with the prior art in industrial fiber drawing processes become evident:

1. The invented method and apparatus provide the fiber drawing in industrial environment at low fiber speed V_{fiber} and, at the same time, maintain fiber outlet speed V_{outlet} and fiber take-up speed $V_{take\text{-}up}$ at regular industrial level ranging from several hundred to several thousand meters per minute providing high throughput. The ratio of speed V_{outlet} to speed $(V_{fiber})_{max}$ is substantially greater than 1 to 1 ranging from about 10 to 1 to about 6000 to 1. This accomplishment results in some other advantages presented below.

2. The invented method and apparatus provide the uniform fiber drawing in industrial high-throughput process at low strain rate V_{strain}, i.e., about 6-70 %/s, and high drawing time T, i.e., it can reach tens of seconds. This long drawing time is necessary to heat the fiber to the elevated ambient temperature with low temperature gradient in the fiber cross-section during the drawing in order to have uniform morphology and physical properties in the cross-section.

3. The low-strain-rate, long-drawing-time invented method and apparatus provide more reliable industrial process for continuous uniform drawing of polymer fibers without abrupt, "impulsive" acceleration resulting in lower tension in the drawing line, less breaks, less equipment stops, and less waste than in the prior art.

4. The invented method and apparatus for continuous fiber drawing provide high-throughput industrial process producing dimensionally stable, low-shrinkage fibers without using expensive and energy-consuming additional equipment and without reducing physical properties, such as initial modulus, intermediate moduli, and tenacity. This may result in substantial saving of capital expenses, energy consumption, and possibility of smaller industrial space.

5. The invented method and apparatus provide industrial continuous process for drawing of polymer fiber (both aliphatic and wholly-aromatic) capable of improving their tensile properties (i.e., tenacity, Young modulus, intermediate moduli, etc.) approaching those obtained in laboratory experiments. This method is the missing link in development of a new generation of low-cost, high-performance industrial polymer fibers (most probably melt-spun, regular-molecular-weight, aliphatic) having tenacity of about 1-2 GPa (12-22 gm/denier) and initial tensile modulus of about 20-100 GPa (250-1000 gm/denier) for different polymer fibers having different theoretical values of tensile properties. Thus, for the new generation of industrial melt-spun, aliphatic polymer fibers, tenacity can be by 2.0-3.0 times higher and initial moduli can be by several times higher than those for conventional commercial aliphatic polymer fibers.

6. The invented method and apparatus in some cases can provide a substantial increase in the throughput in comparison with the existing industrial processes by increasing outlet V_{outlet} and take-up $V_{take\text{-}up}$ speeds and, at the same time, maintaining improved physical properties, such as initial modulus, intermediate moduli, tenacity, and shrinkage mentioned above. The outlet and take-up speeds can be 4500-6000 m/min and more.

Conclusion, Ramifications, and Scope.

Thus the reader can see that the fiber drawing method and apparatus of this invention can be used to produce industrial fibers at fiber speed $(V_{fiber})_{max}$ substantially lower than outlet speed V_{outlet} and take-up speed $V_{take\text{-}up}$ and at substantially lower strain rate V_{strain}, lower tension in the fiber drawing line, and longer drawing time T than in the prior art without reducing throughput. This forms a basis for achieving some unprecedented results, i.e., producing industrially polymer fibers with improved tensile and other physical properties approaching those obtained in laboratory experiments. This means that the development of a new generation of low-cost, high-performance, aliphatic industrial polymer fibers is feasible. On the one hand, tenacity of the new fibers can be 1/3-1/2 of that of high-cost, high-strength, high-modulus Kevlar 49 and Spectra fibers discussed above. On the other hand, the tenacity can be two times and more greater than

that of low-cost, low-performance commercial aliphatic polymer fibers. Initial modulus and intermediate moduli can be increased even greater.

Furthermore, this invented method offers additional advantages.

The invented method resolves another fundamental problem of the fiber technology -- how to produce industrial fibers having substantially improved both tensile properties and dimensional stability (low shrinkage) in the high-throughput process without utilizing special heat-setting equipment. This may result in substantial saving in capital expenses, and possibility of a smaller industrial space.

It also provides a more reliable process which has less breaks, less equipment stops, and less waste, resulting in substantial saving.

While the above description contains many specifics, these should not be considered as limitations on the scope of the invention, but rather as an exemplification of the presented embodiments thereof. Many other variations are possible. For example:

1. The winding and unwinding flyers are located outside the heat chamber, while the heat chamber surrounds the greatest part of the conveyer-drawing members.

2. The invented drawing apparatuses can be arranged in a series or other treating devices may be provided between two drawing apparatuses of the invention; a consecutive arrangement of two or more invented apparatuses is especially advantageous for achieving the total draw ratios 10 to 1 and higher, like in the case of gel spinning of ultra-high molecular weight polymers, or providing different drawing temperatures at different stages of drawing.

3. A conventional stage of drawing using cylindrical draw rollers may precede or follow the invented apparatus; the rollers may be used for fine and minute adjustment of the total draw ratio; the draw rollers may be constructed with or without internal heaters.

4. In the embodiment illustrated in Fig. 1A each spindle is replaced by several consecutive rotating spindles connected by universal joints and arranged either at different or same divergence angles α.

5. In an another embodiment each conveyer-drawing member (e.g., the threaded spindle or the chain) consists of three sections. In section I they are arranged in parallel to the central axis, in section II they diverge from the central axis (as in the embodiments illustrated in Figs. 1A, 2A and 3A), and in section III they are arranged in parallel to the central axis again. Sections I and III are outside of the heat chamber, their transfer points with section II being arranged right before and right after the heat chamber respectively. Section II is predominantly inside of the heat chamber (at least 85% of its path is inside of the chamber). That prevents the temperature of the conveyer-drawing members in section II from falling substantially below the temperature of the heat chamber when they leave the chamber. The fiber is wound in successive fiber loops about the conveyer-drawing members by the fiber winding device in the beginning of section I, moved along sections I-III, and unwound at the end of section III by the unwinding device. In this arrangement the fiber enters the heat chamber in controlled loops and cools down in controlled loops after the heat chamber. The conveyer-drawing members in section II could be subdivided into two or more sections which are arranged consecutively at transfer points.

6. In the embodiment of Fig. 1A the threaded spindles are conical with diameter increased toward the delivery ends. Each point of the fiber loops rotates about the central axis with increasing linear speed while moving from the receiving to delivery ends. Optimization of this effect can result in better uniformity of the drawn fiber.

7. In the embodiments of Figs. 1A-3A, a stepping electric motor is used to drive the conveyer-drawing members (the threaded spindles, endless chains, etc.), the winding flyer, and the unwinding flyer.

8. In an another embodiment, the conveyer-drawing members are cantilever having either the delivery or receiving ends free, with no support. This is an alternative design to the embodiments of Figs. 1A-3A having some advantages in taking the fiber off the apparatus or feeding the fiber to the apparatus. In the case of the cantilever conveyer-drawing members having free delivery ends, the leading fiber loop can be taken off from the delivery ends by the take-off mechanism without the unwinding flyer.

9. In the embodiment of Fig. 1A some of the threaded spindles rotate in a direction opposite to the direction of rotation of the other spindles. Oppositely rotating spindles have opposite threads. For example, the spindles rotating in one direction have right hand thread and the spindles rotating in the opposite direction have left hand thread. Consequently, all spindles transport the fiber thereon in the same direction, but since opposite forces are exerted by oppositely rotating threaded spindles in circumferential direction on the fiber, the coiled fiber loops are not rotated as a whole about the central axis.

10. In the embodiment of Fig. 3A rollers 98 have tracer pins attached to their lateral surfaces instead of gears 100. These pins slide along specially profiled stationary slots, while rolls 98 are moved from the receiving to delivery ends, and turn rollers 98. Therefore, gears 84, 86, and 90 and shaft 88 are not installed.

11. In the embodiments of Figs. 2A and 3A, circulating endless cables, belts, bands, cords, or escalator-type moving stairs can be used as the conveyer-drawing members instead of the chains.

12. In the embodiments of Figs. 2A and 3A, the displacing means comprise guide plates, rods or pins mounted on the chains, cables, belts, bands, cords, or escalator-type moving stairs instead of the rollers and the guide semi-rings.

13. The fiber draw ratio can be changed, in addition to that presented in the embodiments of Figs. 1A-3A, by changing positions along the central axis where the fiber is received on the conveyer-drawing means and/or taken off from the conveyer-drawing means, circumferences of

the first fiber loop at the receiving ends and/or the leading fiber loop at the delivery ends being changed respectively.

14. The fiber draw ratio can be changed, in addition to that presented in the embodiments of Figs. 1A-3A, by adjusting the distance between the delivery ends and the central axis, circumference of the leading fiber loop being changed.

15. In the embodiments of Figs. 1A-3A, the fiber can be treated, while being drawn, using hot plates or baths of active media instead oh the heat chambers.

Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their legal equivalents.

APPENDIX

Designations for symbols

λ	Draw ratio, i.e., the extent of the fiber drawing
V_{fiber}	Linear speed along the fiber axis of fiber points in the process of drawing; in the invented drawing apparatus the speed is different for different fiber points of each fiber section being drawn between two adjacent conveyer-drawing members
V_{fiber1}	Speed V_{fiber} in the beginning of the fiber drawing
V_{fiber2}	Speed V_{fiber} at the end of the fiber drawing
$V_{surface1}$	Linear surface speed of the feed rollers (in the case of drawing by rotating rollers)
$V_{surface2}$	Linear surface speed of the receiving rollers (in the case of drawing by rotating rollers)
$(V_{fiber})_{max}$	The highest value of fiber speed V_{fiber} in the drawing process
V_{fiberK} and V_{fiberP}	Speed V_{fiber} of fiber points K and P (Fig. 5) in the invented drawing apparatus
V_{intlet}	Fiber inlet speed, which is a fiber linear speed along the fiber axis of feeding the fiber to the invented drawing apparatus
V_{outet}	Fiber outlet speed, which is a fiber linear speed along the fiber axis of conveying the drawn fiber from the drawing stage either to the next stage of the continuous fiber making process or to the receiving package.
$V_{take\text{-}up}$	Take-up speed, which is a fiber linear speed along the fiber axis of taking-up the drawn fiber on the receiving package
V_{strain}	Strain rate, which is a relative deformation of the fiber (strain) in a unit time
T	Time of drawing
V_{loop}	Speed of conveying of the fiber loops along the central axis
d	Distance between adjacent loops in the fiber coil along the central axis, i.e.,

	a pitch of the fiber coil
Δt	Time needed for the fiber loop to pass distance d
L	Circumference of the leading fiber loop at the delivery ends
L'	Circumference of the first fiber loop at the receiving ends
n	Number of the conveyer-drawing members
A	Ratio V_{outlet}/V_{loop} ($V_{take\text{-}up}/V_{loop}$ where $V_{outlet} = V_{take\text{-}up}$)
B	Ratio $V_{outlet}/(V_{fiber})_{max}$
α	Divergence angle -- angle between the conveyer-drawing members and the central axis of the apparatus
L_{fiber}	Distance which each point of the fiber loop passes in the process of rotation of the loop about the central axis while the loop as a whole passes distance d along the central axis for time Δt
L_{total}	Total distance which each point of the fiber loop passes in the process of rotation of the loop about the central axis while the loop as a whole passes from the receiving up to delivery ends
$L_{average}$	Average circumference of the fiber loops in the heat chamber
L_i and L_{i+1}	Circumferences of two adjacent fiber loops
N	Number of the fiber loops in the heat chamber
N'	Number of the fiber loops with the average circumference $L_{average}$ which have the total circumference equal to $L_{total.}$
M	Length of the fiber coil along the central axis
$V_{rotation}$	Fiber linear speed of each point of the fiber loop in the case of rotation of the coiled fiber loops about the central axis
$D_{spindle}$	Inner diameter of the thread of the spindle